Electronic Supplementary Material (ESI) for Energy & Environmental Science.

Supplemental Information

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1 Pathway-specific results and assumptions

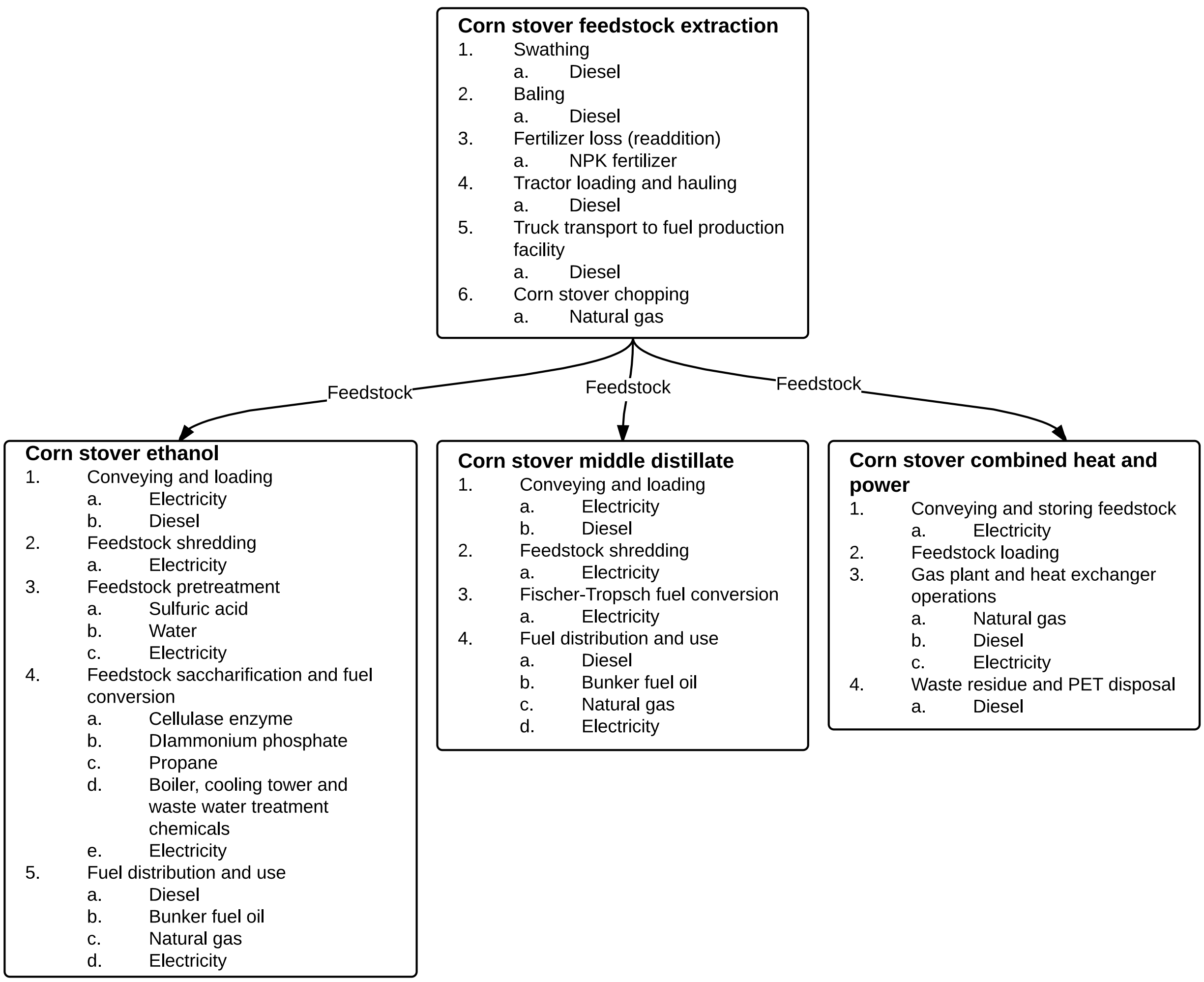

Figure 1: Pathway-specific lifecycle steps for corn stover end uses

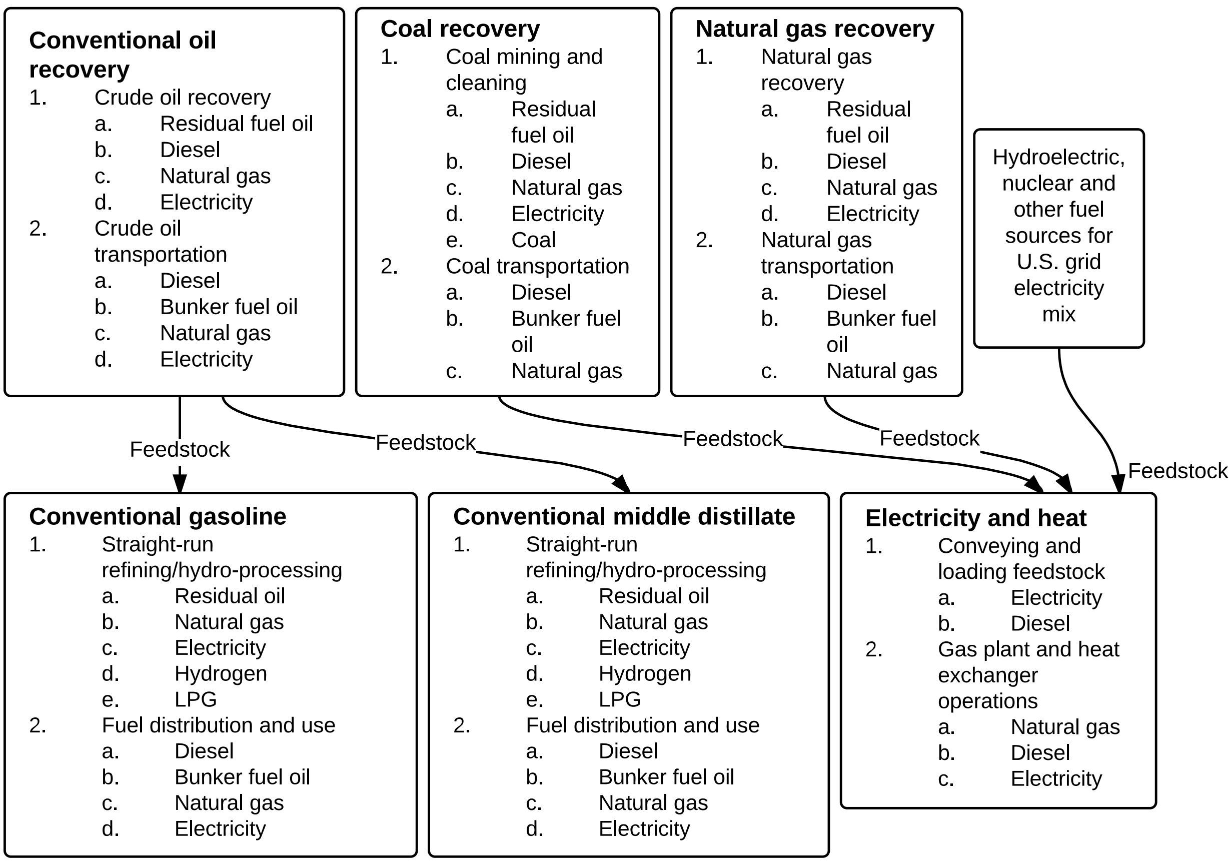

Figure 2: Pathway-specific lifecycle steps for conventional fuels and power

1.1 Electricity and Heat

1.1.1 CHP from corn stover

Assumptions for heat and power production in CHP systems is tabulated below. Low, mode and high values for the triangular probability distributions are presented in Table 1.

Table 1: Cost and performance of CHP systems

Parameter	Low	Mode	High
CHP rating (MW)	10	25	40
Overall efficiency (%)	70	75	80
Capital cost (M$)	7.5	28.8	50.0
Operating cost (cents/kWh)	0.5	0.49	0.42

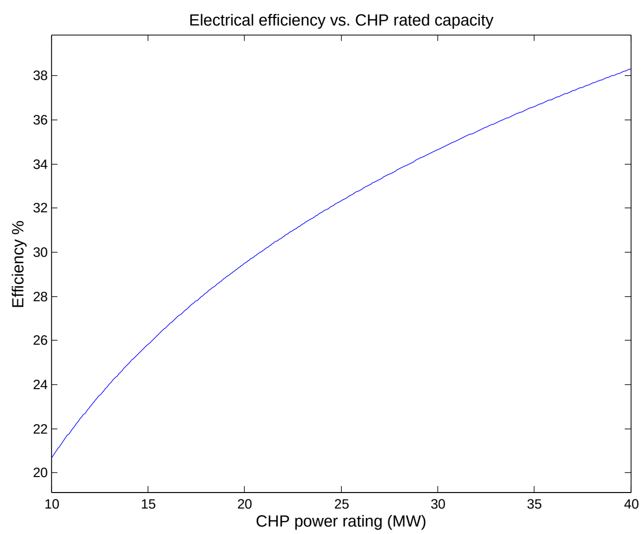

Figure 3: Efficiency against capacity of CHP systems

Delivered dry corn stover is chopped, prior to being transported on a conveyor belt and stored. The feedstock is then loaded into the incineration or gasification facility. We assume the biomass credit from corn stover to offset combustion CO_2 emissions. The GHG emissions from waste disposal at the facility are accounted for. Capital costs for CHP generation are scaled linearly (coupled uncertainty) based on rated plant capacity in the Monte-Carlo framework.

1.1.2 U.S. grid average electricity

United States grid average emissions are calculated based on the electricity fuel mix [1]. The low, baseline, and high GHG profiles calculated using GREET are tabulated below.

Table 2: GHG emissions and profile: U.S. electric grid

Feedstock share (%)	Low	Mode	High
Coal	37	46	49
Natural gas	30	22.7	20
Nuclear (M$)	19	20.3	20.3
Fuel oil	0.9	0.9	0.9
Biomass	0.5	0.3	–
Other (renewable)	12.6	9.8	9.8
GHG emissions (gCO_{2e}/MJ)	170.7	186.2	190.7

1.1.3 Results – CHP from corn stover

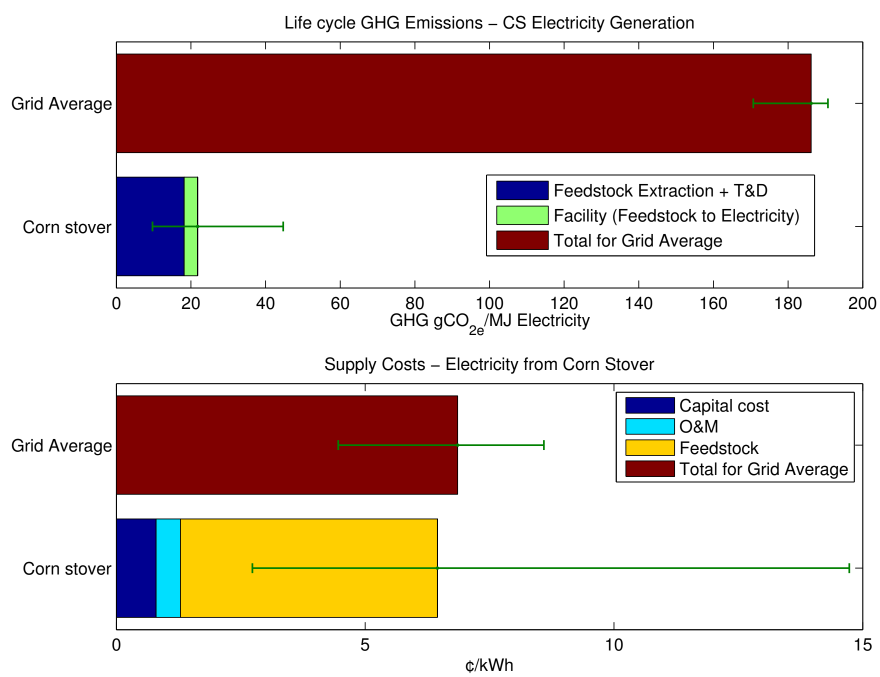

Figure 4: Lifecycle GHG emissions and supply costs for electricity generation

Table 3: Lifecycle GHG emissions and supply costs

	Low	Mean	High
GHG emissions (gCO2e/MJ)			
Total for CHP electricity	15.5	20.4	28.2
Total for U.S. grid	173.5	182.5	189.1
Supply cost (cents/kWh)			
Capital cost	0.64	0.79	0.86
O&M	0.43	0.47	0.50
Feedstock	3.46	4.71	6.47
Total for CHP	4.75	5.96	7.62
Total for U.S. grid	4.98	6.66	8.18

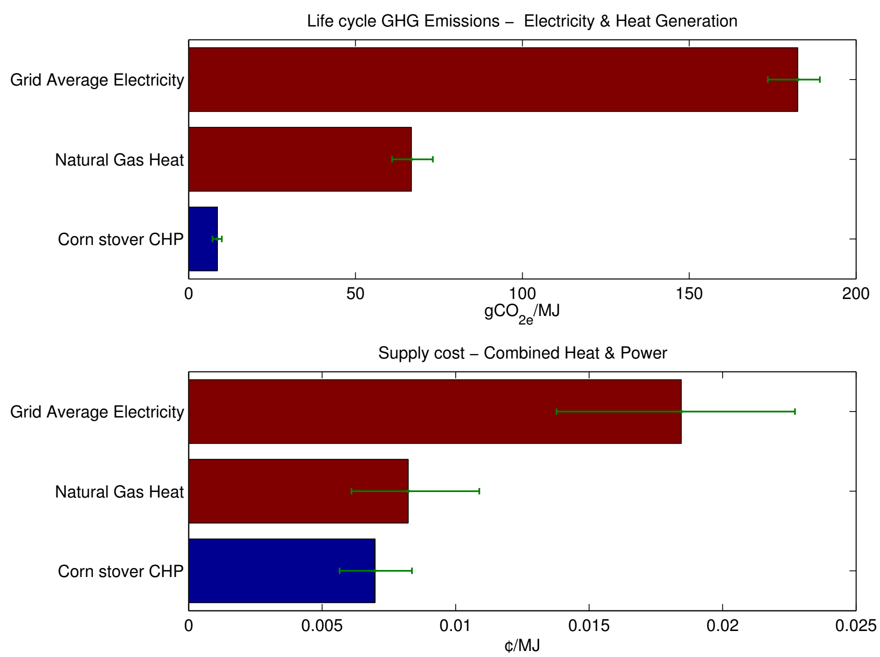

Figure 5: Lifecycle GHG emissions and supply costs for combined heat and power generation

1.2 Ethanol and U.S. gasoline

1.2.1 Ethanol from corn stover

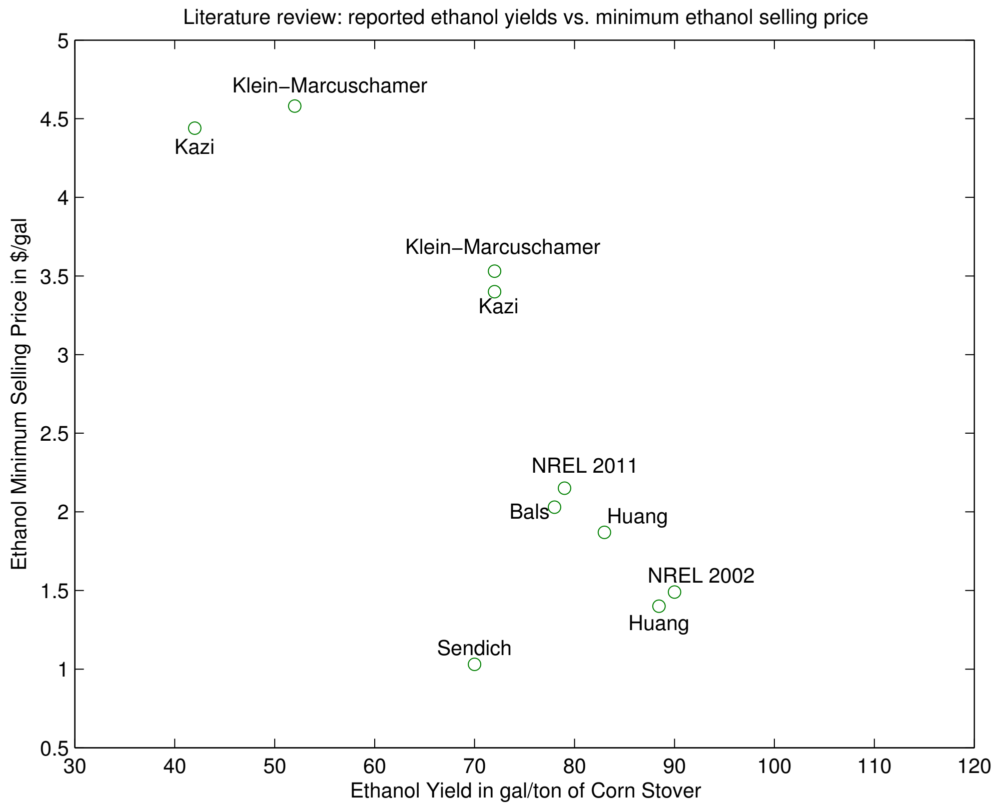

Figure 6: Review of ethanol yields reported in literature [2–8]

Table 4: Cost and performance of Ethanol Production

Parameter	Low	Mode	High
Ethanol yield (gal/ton)	42	79	90
Capital cost (M$)	351.2	468.3	585.3
Operating cost ($/gal)	0.70	1.53	3.73

Ethanol is assumed to be transported within the U.S. using barge (40% by mass, 520 mi), rail (40%, 800 mi), and truck (20%, 80 mi) to bulk terminals, prior to being distributed to pumps via truck (30 mi).

1.2.2 U.S. conventional gasoline

Table 5: Cost and performance of U.S. gasoline production

Parameter	Low	Mode	High
Refining efficiency (%)	85.1%	90.6%	96.1%
Brent crude price ($/bbl)	79.61	111.63	143.65
Crude transport cost ($/bbl)	2.00	3.00	4.00
Gasoline spot price ($/bbl)	86.23	118.23	150.23

1.2.3 Results – ethanol from corn stover

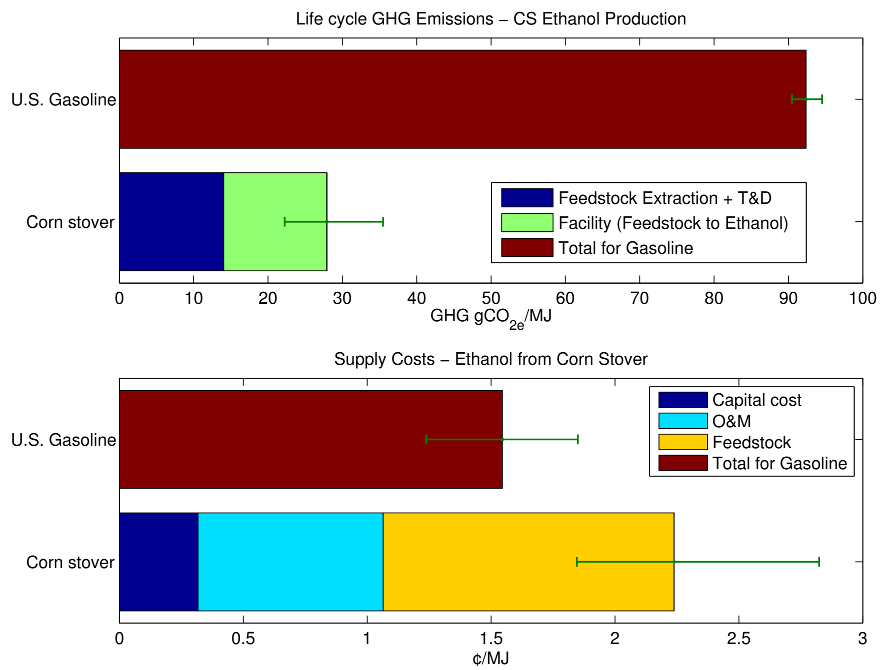

Figure 7: Lifecycle GHG emissions and supply costs for ethanol production

Table 6: Lifecycle GHG emissions and supply costs

	Low	Mean	High
GHG emissions (gCO2e/MJ)			
Total for ethanol	22.2	27.9	35.4
Total for gasoline	90.5	92.4	94.5
Supply cost ($/gal)			
Capital cost	0.21	0.26	0.31
O&M	0.50	0.60	0.70
Feedstock	0.66	0.95	1.41
Total for ethanol	1.49	1.81	2.28
Total for gasoline	1.52	2.27	1.89

1.3 Fischer-Tropsch MD and U.S. conventional MD

1.3.1 FT MD from corn stover

We assess FT MD production in a 5000 barrel per day facility, with a 20 year lifetime. Key parameters are tabulated in Table 7. Operating costs are assumed to be 5% of plant capital costs [9].

Table 7: Cost and performance of Fischer-Tropsch MD production

Parameter	Low	Mode	High
FT synthesis efficiency (%)	42	45	52
Capital cost (thousand $/bpd)	68	213.5	408

FT MD is assumed to be transported within the U.S. using barge (33% by mass, 520 mi), rail (7%, 800 mi), and pipeline (60%, 400 mi) to bulk terminals, prior to being distributed to pumps via truck (30 mi).

1.3.2 U.S. conventional MD

Table 8: Cost and performance of U.S. MD production

Parameter	Low	Mode	High
Refining efficiency (%)	88%	91%	98%
Brent crude price ($/bbl)	79.61	111.63	143.65
Crude transport cost ($/bbl)	2.00	3.00	4.00
MD spot price ($/bbl)	90.26	128.35	166.45

1.3.3 Results – FT MD from corn stover

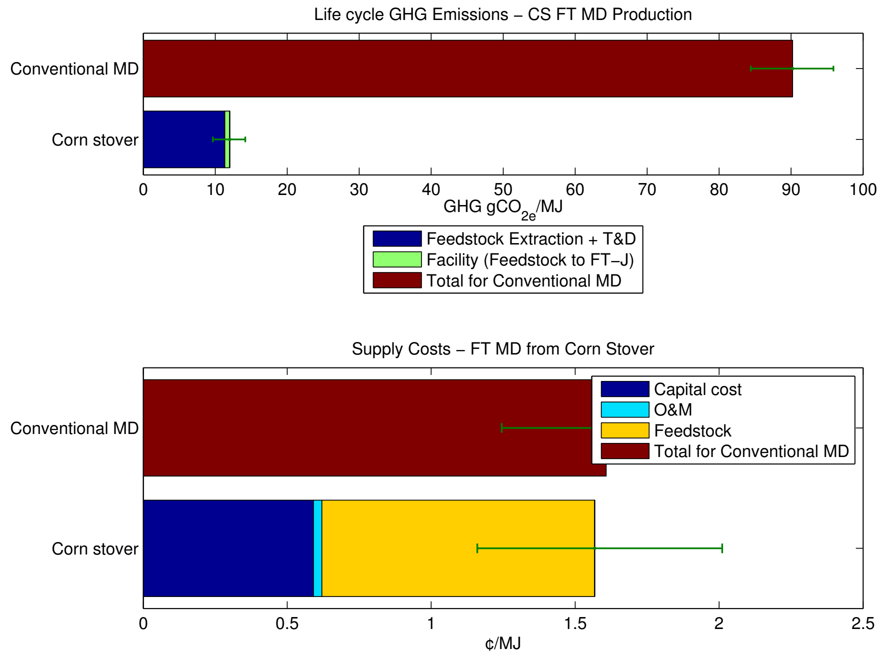

Figure 8: Lifecycle GHG emissions and supply costs for FT MD production

Table 9: Lifecycle GHG emissions and supply costs

	Low	Mean	High
GHG emissions (gCO2e/MJ)			
Total for FT MD	9.7	12.0	14.2
Total for conventional jet	84.4	90.2	95.9
Supply cost ($/gal)			
Capital cost	0.34	0.75	1.20
O&M	0.02	0.04	0.06
Feedstock	0.92	1.20	0.92
Total for FT MD	1.46	1.99	2.54
Total for conventional jet	1.63	2.11	2.59

1.4 Advanced Fermentation MD

1.4.1 AF MD from corn stover

Advanced fermentation MD production is modeled in a 4000 barrel per day facility, based on Staples et al. (2014) [10]. Key process assumptions and costs are outlined in Table 10.

Table 10: Cost and performance of Advanced Fermentation MD production

Parameter	Low	Mode	High
Pretreatment method	Aq. ammonia	Dilute alkali	Dilute acid
Metabolic efficiency (C6 sugars)	80% C6 sugars	85% C6 sugars	90% C6 sugars
Metabolic efficiency (C5 sugars)	50% C5 sugars	60% C5 sugars	70% C5 sugars
Capital cost (M$)	487.5	629.9	1,356.3
Operating cost ($/gal)	1.20	1.90	4.36

1.4.2 Results – AF MD from corn stover

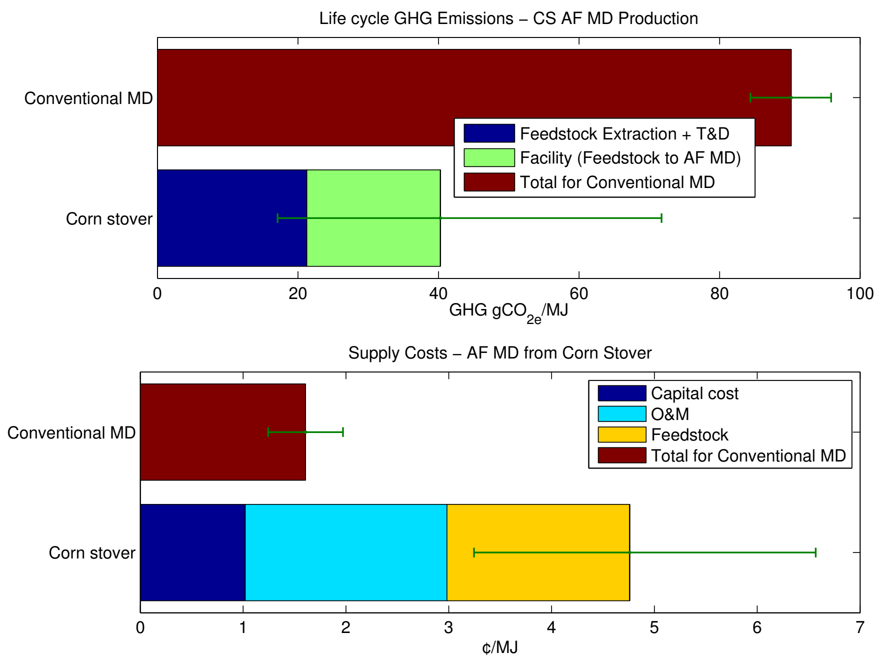

Figure 9: Lifecycle GHG emissions and supply costs for AF MD production

Table 11: Lifecycle GHG emissions and supply costs

	Low	Mean	High
GHG emissions (gCO2e/MJ)			
Total for AF MD	17.1	40.3	71.8
Total for conventional jet	84.4	90.2	95.9
Supply cost ($/gal)			
Capital cost	0.48	1.29	2.54
O&M	1.44	2.48	3.91
Feedstock	1.24	2.25	3.65
Total for AF MD	4.10	6.02	8.30
Total for conventional jet	1.63	2.11	2.59

1.5 Summary of results

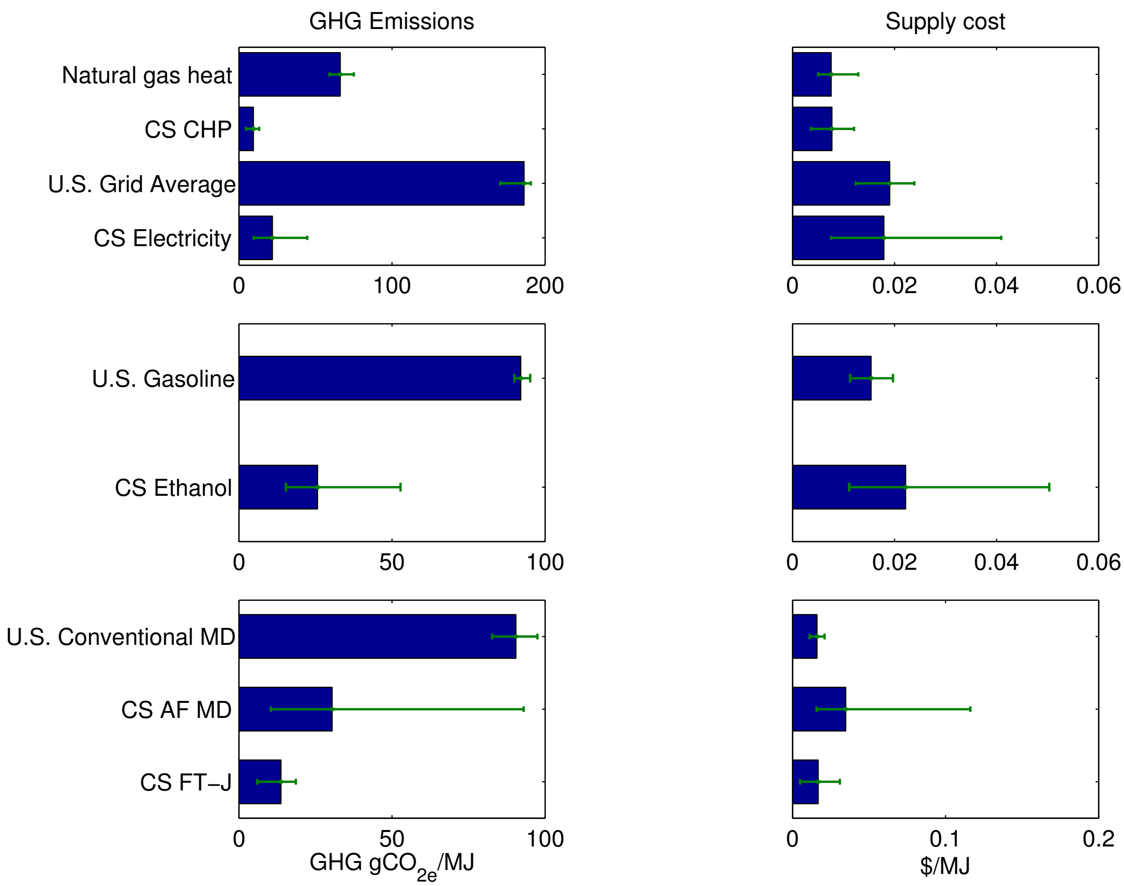

Figure 10: Summary of lifecycle GHG emissions and supply costs

2 Aviation Porfolio Management Tool (APMT)

The Aviation Environmental Portfolio Management Tool (APMT) was developed at MIT to analyze the environmental impacts of proposed policy actions. The model includes individual modules for environmental impact assessment, namely, air quality, noise and a climate impact module. The climate impact module uses an impulse-response approach to evaluate the change in Earth's mean surface temperature, due to the net radiative forcing effect of GHG emissions. The model then evaluates the ecological, health and welfare impacts due to the mean surface temperature change, in terms of the net present value of climate damages [11]. The analytic framework for assessing climate costs in APMT is derived from the Dynamic Integrated model of Climate and the Economy [12]. Damage functions are used to translate environmental impacts into monetized societal costs, using a fixed discount rate. The damage function is estimated using damage curves for 12 global regions. Monetized effects include the impacts on agriculture, health impacts and damages due to a rising sea-level, among other damages. The model does not account for all possible damages — fragile ecosystem damage, for instance, is neglected [13]. APMT has been used in prior archival journal studies to assess the climate [14, 15], air quality [16] and health and welfare impacts of aviation activity [11, 17].

3 Monte-Carlo analysis

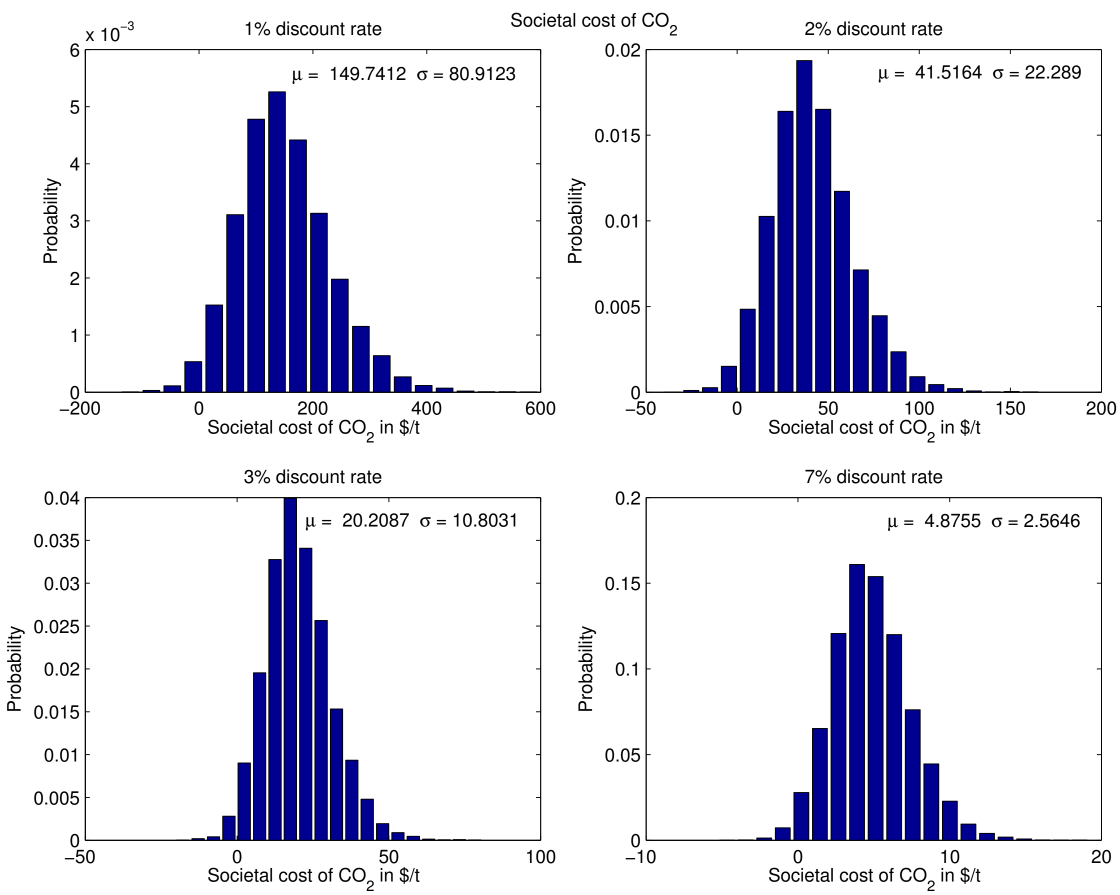

Figure 11: Probability distributions - societal cost of CO_2 for discount rates of 1–7%

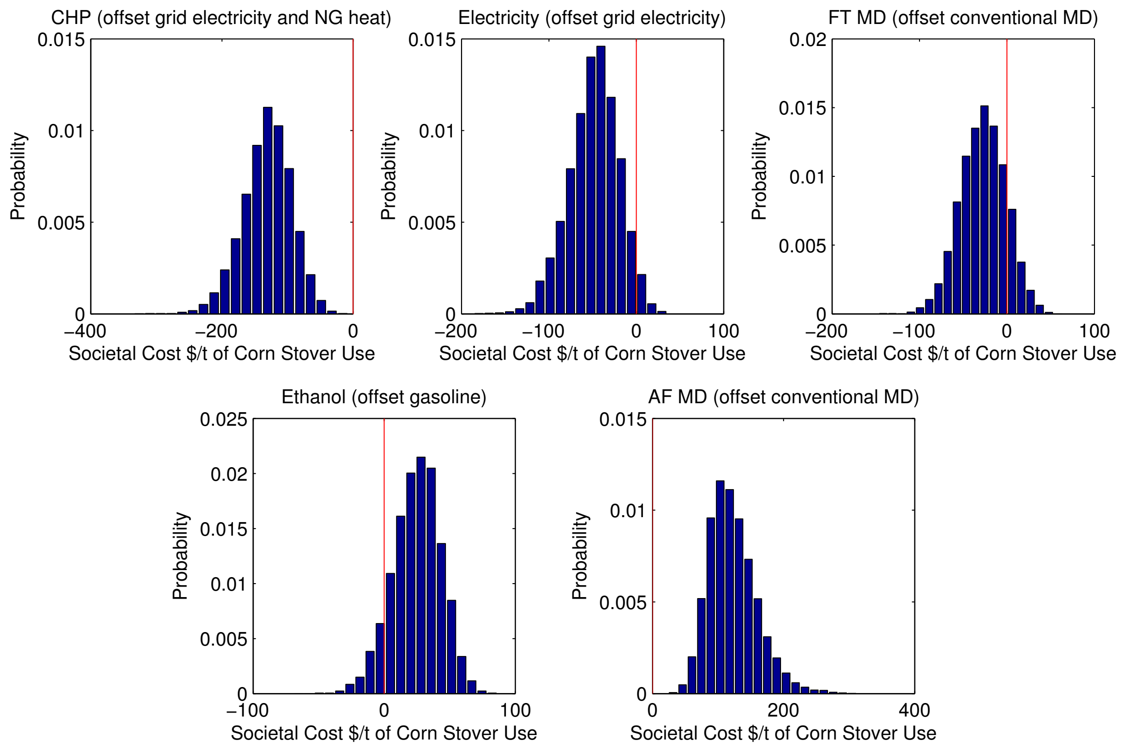

Figure 12: Probability distributions of societal cost results (2% discount rate for climate cost)

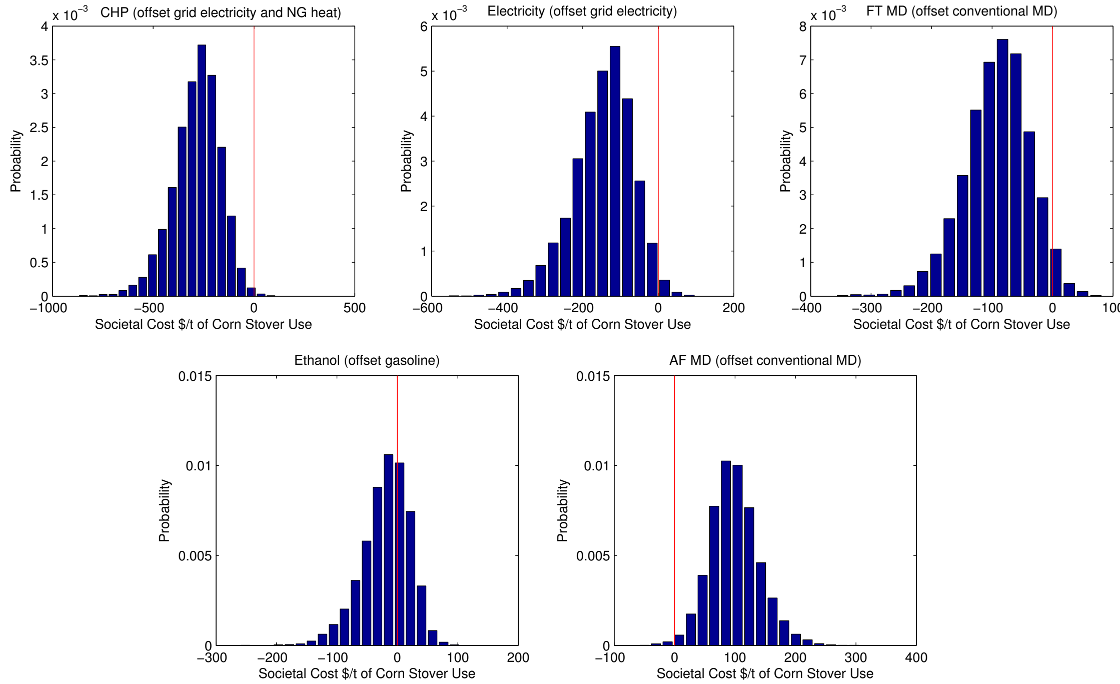

Figure 13: Probability distributions of societal cost results (1% discount rate for climate cost)

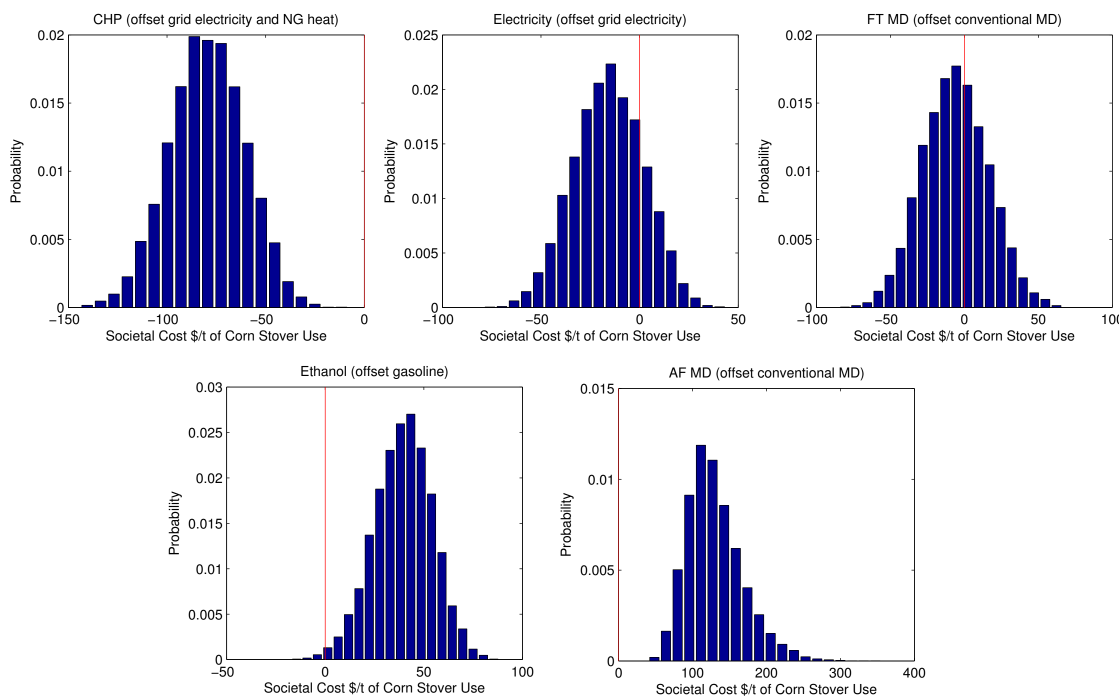

Figure 14: Probability distributions of societal cost results (7% discount rate for climate cost)

References

[1] U.S. Energy Information Administration (EIA). Electricity Net Generation, 2012. URL http://www.eia.gov/totalenergy/data/annual/index.cfm#electricity.

[2] Feroz Kabir Kazi, Joshua a. Fortman, Robert P. Anex, David D. Hsu, Andy Aden, Abhijit Dutta, and Geetha Kothandaraman. Techno-economic comparison of process technologies for biochemical ethanol production from corn stover. *Fuel*, 89: S20–S28, November 2010. ISSN 00162361. doi: 10.1016/j.fuel.2010.01.001. URL http://linkinghub.elsevier.com/retrieve/pii/S0016236110000025.

[3] Daniel Klein-Marcuschamer, Piotr Oleskowicz-Popiel, Blake A. Simmons, and Harvey W. Blanch. Technoeconomic analysis of biofuels: A wiki-based platform for lignocellulosic biorefineries. *Biomass and Bioenergy*, 34(12):1914–1921, December 2010. ISSN 09619534. doi: 10.1016/j.biombioe.2010.07.033. URL http://www.sciencedirect.com/science/article/pii/S0961953410002576.

[4] D. Humbird, R. Davis, L. Tao, C. Kinchin, D. Hsu, and A. Aden. Process Design and Economics for Biochemical Conversion of Lignocellulosic Biomass to Ethanol Process Design and Economics for Biochemical Conversion of Lignocellulosic Biomass to Ethanol. Technical Report May, National Renewable Energy Laboratory, Golden, Colorado, 2011.

[5] A Aden, M Ruth, K Ibsen, J Jechura, K Neeves, J Sheehan, B Wallace, L Montague, A Slayton, and J Lukas. Lignocellulosic Biomass to Ethanol Process Design and Economics Utilizing Co-Current Dilute Acid Prehydrolysis and Enzymatic Hydrolysis for Corn Stover Lignocellulosic Biomass to Ethanol Process Design and Economics Utilizing Co-Current Dilute Acid Prehyd. Technical Report June, National Renewable Energy Laboratory, Golden, Colorado, 2002.

[6] Bryan Bals, Chris Wedding, Venkatesh Balan, Elizabeth Sendich, and Bruce Dale. Evaluating the impact of ammonia fiber expansion (AFEX) pretreatment conditions on the cost of ethanol production. *Bioresource Technology*, 102(2):1277–83, January 2011. ISSN 1873-2976. doi: 10.1016/j.biortech.2010.08.058. URL http://www.sciencedirect.com/science/article/pii/S0960852410014185.

[7] Elizabeth Newton Sendich, Mark Laser, Seungdo Kim, Hasan Alizadeh, Lizbeth Laureano-Perez, Bruce Dale, and Lee Lynd. Recent process improvements for the ammonia fiber expansion (AFEX) process and resulting reductions in minimum ethanol selling price. *Bioresource Technology*, 99(17):8429–35, November 2008. ISSN 0960-8524. doi: 10.1016/j.biortech.2008.02.059. URL http://www.sciencedirect.com/science/article/pii/S0960852408002484.

[8] Hua Jiang Huang, Shri Ramaswamy, Waleed Al-Dajani, Ulrike Tschirner, and Richard A. Cairncross. Effect of biomass species and plant size on cellulosic ethanol: A comparative process and economic analysis. *Biomass and Bioenergy*, 33:234–246, 2009. ISSN 09619534. doi: 10.1016/j.biombioe.2008.05.007.

[9] Matthew Pearlson, Nick Carter, Michael Bredehoeft, Christoph Wollersheim, Hakan Olcay, James Hileman, Steven Barrett, and Robert Malina. HEFA and F-T jet fuel cost analyses. In *Commercial Aviation Alternative Fuels Initiative (CAAFI) Workshop*. U.S. Department of Energy, 2012. URL `http://www1.eere.energy.gov/bioenergy/pdfs/malina_caafi_workshop.pdf`.

[10] Mark D Staples, Robert Malina, Hakan Olcay, Matthew N Pearlson, James I Hileman, Adam Boies, and Steven R H Barrett. Lifecycle greenhouse gas footprint and minimum selling price of renewable diesel and jet fuel from fermentation and advanced fermentation production technologies. *Energy & Environmental Science*, 7 (5):1545–1554, 2014. ISSN 1754-5692. doi: 10.1039/C3EE43655A. URL `http://dx.doi.org/10.1039/C3EE43655A`.

[11] Anuja Mahashabde, Philip Wolfe, Akshay Ashok, Christopher Dorbian, Qinxian He, Alice Fan, Stephen Lukachko, Aleksandra Mozdzanowska, Christoph Wollersheim, Steven R.H. Barrett, Maryalice Locke, and Ian A. Waitz. Assessing the environmental impacts of aircraft noise and emissions. *Progress in Aerospace Sciences*, 47(1):15–52, January 2011. ISSN 03760421. doi: 10.1016/j.paerosci.2010.04.003. URL `http://linkinghub.elsevier.com/retrieve/pii/S0376042110000382http://dx.doi.org/10.1016/j.paerosci.2010.04.003`.

[12] William D. Nordhaus. The 'DICE' Model: Background and Structure of a Dynamic Integrated Climate-Economy Model of the Economics of Global Warming. *Cowles Foundation Discussion Papers*, 1992. URL `http://ideas.repec.org/p/cwl/cwldpp/1009.html`.

[13] Frank Ackerman and Ian J. Finlayson. The economics of inaction on climate change: a sensitivity analysis. *Climate Policy*, 6(5):509–526, 2006. ISSN 1469-3062. doi: 10.1080/14693062.2006.9685617.

[14] Mitch R. Withers, Robert Malina, Christopher K. Gilmore, Jonathan M. Gibbs, Chris Trigg, Philip J. Wolfe, Parthsarathi Trivedi, and Steven R.H. Barrett. Economic and environmental assessment of liquefied natural gas as a supplemental aircraft fuel. *Progress in Aerospace Sciences*, 66:17–36, January 2014. ISSN 03760421. doi: 10.1016/j.paerosci.2013.12.002. URL `http://www.sciencedirect.com/science/article/pii/S0376042113000900`.

[15] Christopher S. Dorbian, Philip J. Wolfe, and Ian a. Waitz. Estimating the climate and air quality benefits of aviation fuel and emissions reductions. *Atmospheric Environment*, 45(16):2750–2759, May 2011. ISSN 13522310. doi: 10.1016/j.atmosenv.2011.02.025. URL `http://linkinghub.elsevier.com/retrieve/pii/S1352231011001592`.

[16] Christopher K Gilmore, Steven R H Barrett, Steve H L Yim, T Murray, Stephen R Kuhn, Amos P K Tai, Robert M Yantosca, Daewon W Byun, Fong Ngan, Xiangshang Li, Jonathan I Levy, Akshay Ashok, Jamin Koo, Hsin Min Wong, Olivier Dessens, Gregg G Fleming, Matthew N Pearlson, Robert Malina, Sarav Arunachalam, S Francis, Eric M Leibensperger, Daniel J Jacob, James I Hileman, and Ian A Waitz. Environmental Cost-Benefit Analysis of Ultra Low Sulfur Jet Fuel. (December), 2011.

[17] PJ Wolfe, SHL Yim, Gideon Lee, and Akshay Ashok. Near-airport distribution of the environmental costs of aviation. *Transport Policy*, ([In Press]), 2014. ISSN 0967070X. doi: 10.1016/j.tranpol.2014.02.023. URL http://www.sciencedirect.com/science/article/pii/S0967070X14000547.